



Proposals Due next Tuesday

- Project Proposal due Tuesday February 15th
- Project review session Thursday February 10th instead of Lab.
 - Review times will be scheduled to avoid waiting
 - Review will be in Building 2 at LBL
 - Erik's office is 2-454
 - Alex's office is 2-419
- No problem set this week. Project preparation and proposal writing instead.





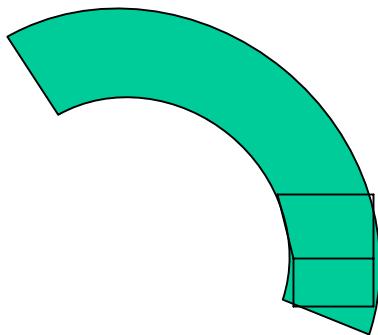
Project discussion Schedule for Thursday

Time	Alex Liddle	Erik Anderson
3:00	Brooke Mesler	Peng Zhang
3:20	Kin-Yip Phoa	Tanner Neville
3:40	Nev Levy	Swanee Shin
4:00	Break	Break
4:10	Maryam Ziae-Moayyed	Alvaro Padilla
4:30	Yuan Wang	Wojtek Poppe





LBNL Digital Pattern Generator for curved structures



How to draw smooth
curved shapes?

Typical PGs will require
rectangles, and trapezoids
only.





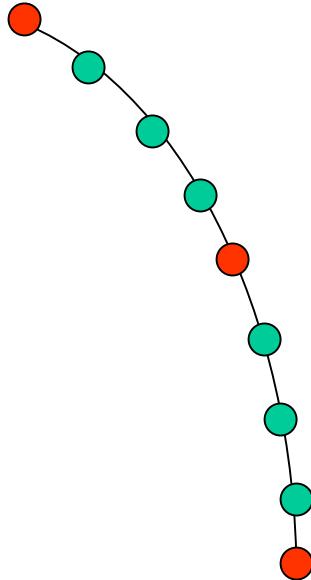
Equation to generate exposure coordinates

$$X(k) = a_0 + a_1 k + a_2 k^2$$

$$Y(k) = b_0 + b_1 k + b_2 k^2$$

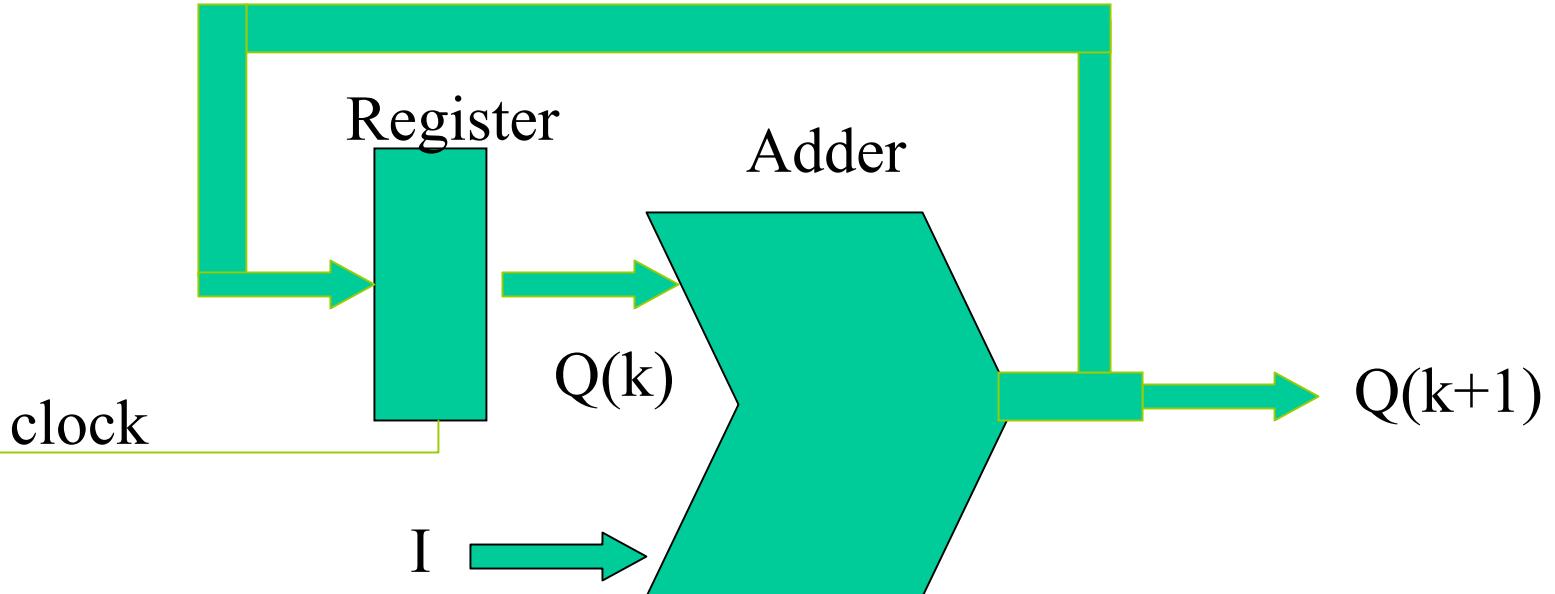
We can always find the 6
coefficients $a_0 \ a_1 \ a_2 \ b_0 \ b_1 \ b_2$

That pass through three distinct
points.





Digital Accumulator = Adder + Register

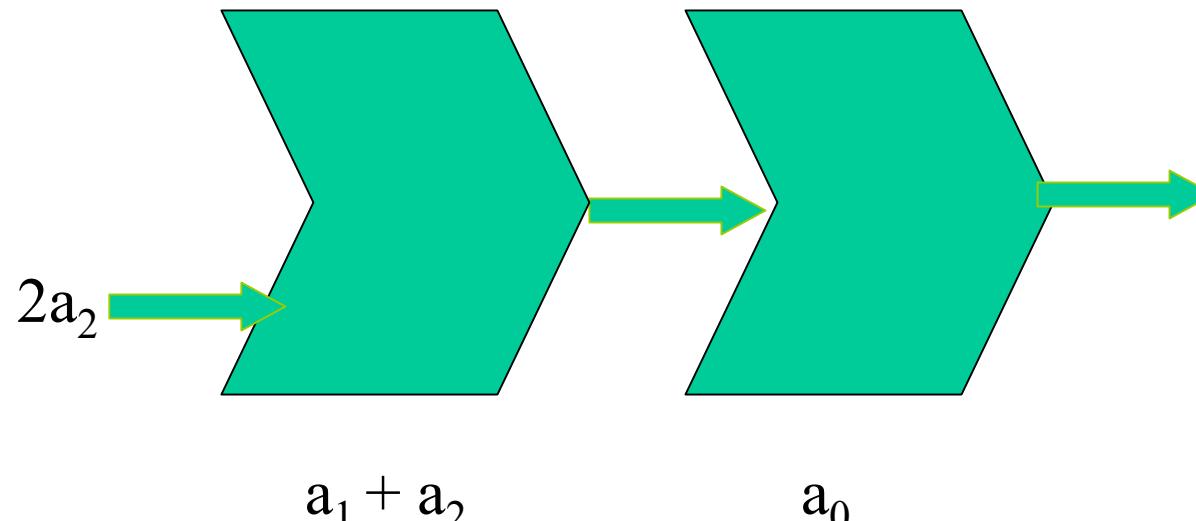


$$Q(k+1) = Q(k) + I$$





Two accumulators produce quadratic function



$$X(k) = a_0 + a_1 k + a_2 k^2$$





Scale and Rotation in Hardware

$$X = a_0 + a_1 X + a_2 Y$$

$$X = b_0 + b_1 X + b_2 Y$$

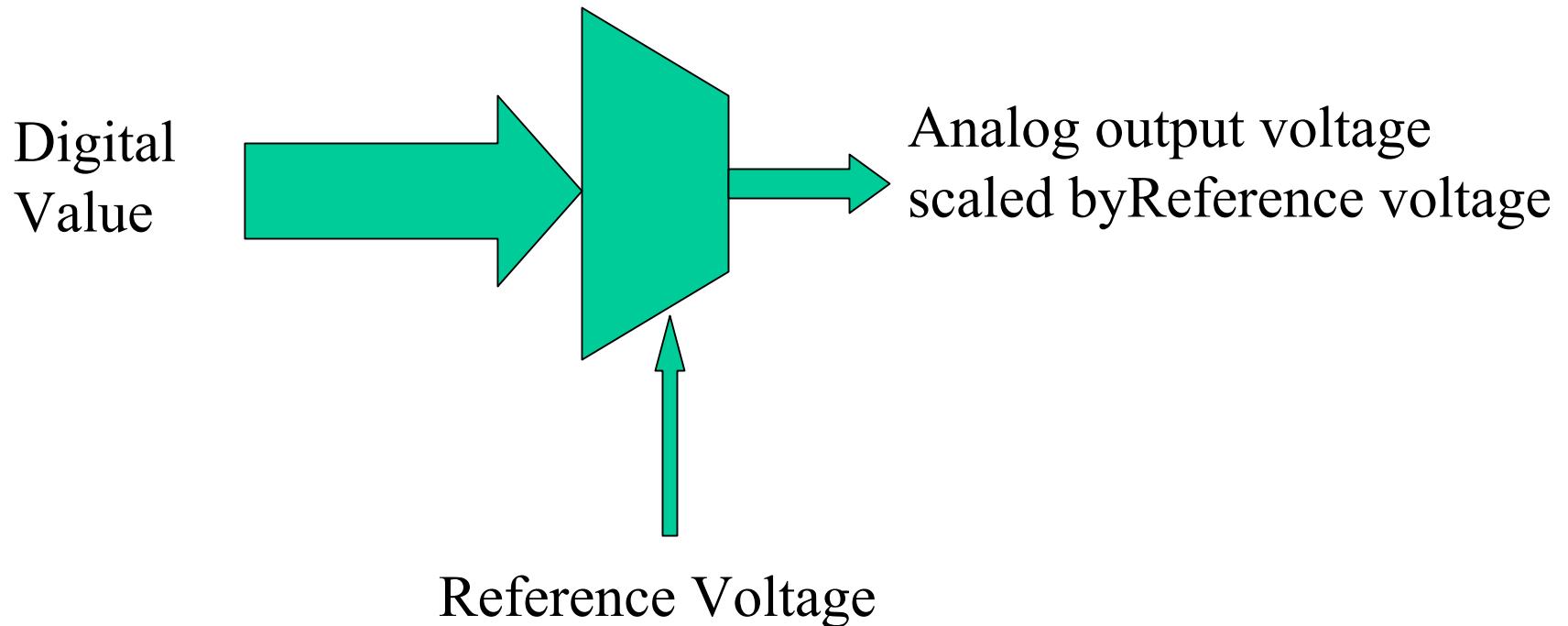
No rotation or scale $a_1=1$, $a_2=0$, $b_1=1$ $b_2=0$

In general this is not true!



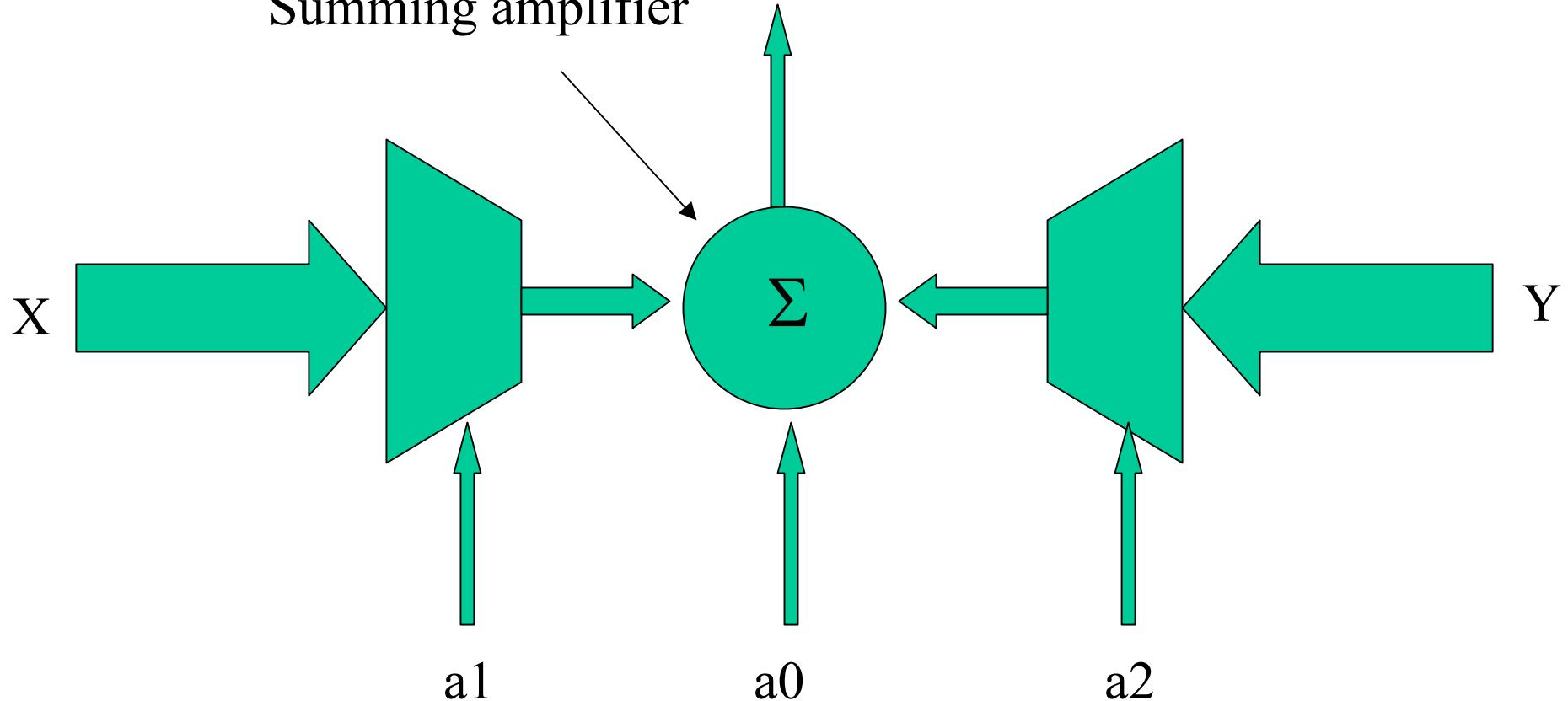


Multiplying Digital Analog Converter (DAC)





Summing amplifier





E298A/EE290B – Electron Optics Basics

- Sources
 - Lenses
 - Deflectors
 - Blankers
 - Resolution
 - Spherical, Chromatic, and Diffraction
 - VB6 Electron Optics Layout
 - Project Proposal
-





Basic Physics for electron Optics



$$F = dp/dt$$

$$p = mv/(1-(v/c)^2) = \gamma mv$$

$$KE + mc^2 = \gamma mc^2 = (m^2c^4 + p^2c^2)^{1/2}$$

$$dp/dt = q(E + v \times B)$$

$$B = \nabla \times A, \nabla \cdot B = 0 \quad B = \mu_0 H \text{ (free space)}$$

$$\nabla \cdot D = \rho \quad D = \epsilon_0 E \text{ (free space)}$$

$$\nabla \times H = J + dD/dt$$

$$\nabla \times E = -dB/dt$$

$$E = h\nu \quad p = h/\lambda$$

$$E = \hbar\omega \quad p = \hbar k$$

$$h = 6.625 \times 10^{-34} \text{ Joule-sec}$$

$$\epsilon_0 = 8.854 \times 10^{-12} \text{ Farad/m}$$

$$\mu_0 = 4\pi \times 10^{-6} \text{ Henry/m}$$

$$c = 2.998 \times 10^8 \text{ meter/sec}$$

$$q = 1.602 \times 10^{-19} \text{ Coul}$$

$$M_{\text{electron}} = 9.11 \times 10^{-31} \text{ Kg}$$





Wavelength of an Electron Non-Relativistic Calculation

Non-relativistic calculation

$$KE = (p^2/2m) \text{ or } p = \sqrt{2m*KE} \text{ and } \lambda = h/p$$

Use 1000eV for example:

$$p = (1000 * 1.6e-19 * 2 * 9.11e-31)^{1/2} = 1.2e-23 \text{ kg*m/sec}$$

$$\begin{aligned}\lambda &= h/p = 6.6250e-34 \text{ kg*m}^2/\text{sec} / (1.2e-23 \text{ kg*m/sec}) \\ &= 3.88e-11 \text{ m or .0388nm}\end{aligned}$$





Wavelength of an Electron Relativistic Calculation



Relativistic Calculation

$$KE + mc^2 = \gamma mc^2 = (m^2 c^4 + p^2 c^2)^{1/2}$$

$$(V^*q + mc^2)^2 - m^2 c^4 = p^2 c^2 \quad V = 1000\text{eV}$$

$$P = \sqrt{(1000*q + mc^2)^2 - m^2 c^4}/c$$

$$= 1.7889\text{e-}022\text{kg*m/sec}$$

$$\lambda = h/p = 6.6250\text{e-}034\text{kg*m}^2/\text{sec} / (1.7889\text{e-}22\text{kg*m/sec})$$

$$\lambda = 3.7035\text{e-}012\text{m or .0037nm}$$





Electron Wavelength as a function of Energy

Unit Meters



Energy	Relativistic	Non-Relativistic
100eV	1.2270e-010	1.2270e-010
1KeV	3.8783e-011	3.8802e-011
10KeV	1.2211e-011	1.2270e-011
50KeV	5.3581e-012	5.4874e-012
100KeV	3.7035e-012	3.8802e-012
200KeV	2.5095e-012	2.7437e-012





Photon Wavelength as a function of Energy



Unit Meters

Energy	Electron	Photon
100eV	1.2270e-010	1.2414e-008
1KeV	3.8783e-011	1.2414e-009
10KeV	1.2211e-011	1.2414e-010
50KeV	5.3581e-012	2.4827e-011
100KeV	3.7035e-012	1.2414e-011
200KeV	2.5095e-012	6.2068e-012

$$\begin{aligned} E &= h\nu \\ &= hc/\lambda \end{aligned}$$





Classical Physics

$$\mathbf{F} = d\mathbf{p}/dt$$

$$\mathbf{p} = m\mathbf{v}/(1-(v/c)^2) = \gamma m\mathbf{v}$$

$$KE + mc^2 = \gamma mc^2 = (m^2c^4 + p^2c^2)^{1/2}$$

$$d\mathbf{p}/dt = q(\mathbf{E} + \mathbf{v} \times \mathbf{B})$$

$$\mathbf{B} = \nabla \times \mathbf{A}, \nabla \cdot \mathbf{B} = 0 \quad \mathbf{B} = \mu_0 \mathbf{H} \text{ (free space)}$$

$$\nabla \cdot \mathbf{D} = \rho \quad \mathbf{D} = \epsilon_0 \mathbf{E} \text{ (free space)}$$

$$\nabla \times \mathbf{H} = \mathbf{J} + d\mathbf{D}/dt$$

$$\nabla \times \mathbf{E} = -d\mathbf{B}/dt$$





Quantum Theory

$$E = h\nu \quad p = h/\lambda$$

$$E = \hbar\omega \quad p = \hbar k$$



E298A/EE290B

Lecture 4: Electron Optics



Useful physical constants

$$h = 6.625 \times 10^{-34} \text{ Joule-sec}$$

$$\epsilon_0 = 8.854 \times 10^{-12} \text{ Farad/m}$$

$$\mu_0 = 4\pi \times 10^{-6} \text{ Henry/m}$$

$$c = 2.998 \times 10^8 \text{ meter/sec}$$

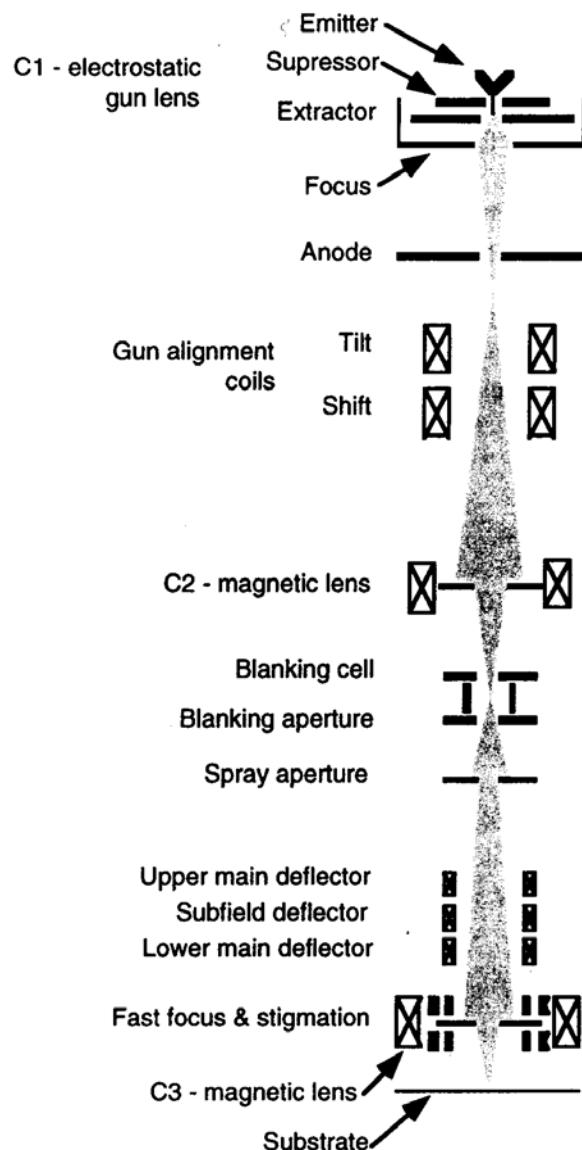
$$q = 1.602 \times 10^{-19} \text{ Coul}$$

$$M_{\text{electron}} = 9.11 \times 10^{-31} \text{ Kg}$$





Electron Optical Layout for the Leica VB6





Electron Optics Basics - Sources

Source

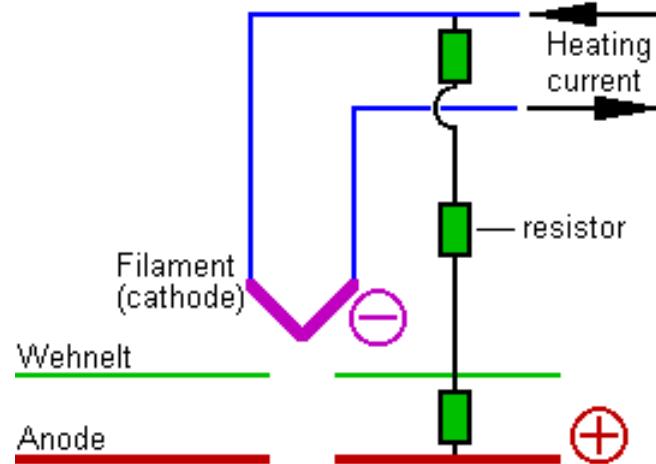
- Tungsten
- LaB_6
- Thermal Field Emmiter (Schottky)
- Cold Field Emmiter



Electron Optics Basics – Sources Thermal

Electron emission, I_s (amps/cm²),
as a function of the absolute
temperature, T , of a
thermionic emitter is given by
Richardson's equation:

$$I_s = AT^2 e^{-(B/T)}$$

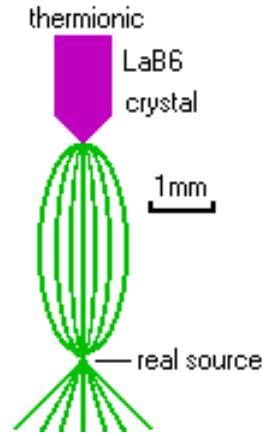


where A and B are constants that
are determined empirically



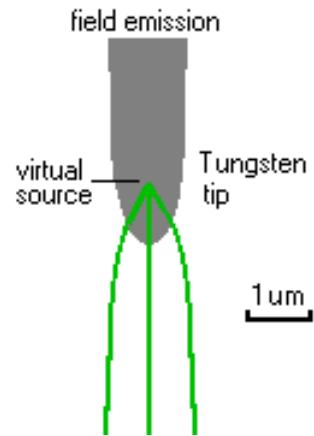


Electron Optics Basics – Sources LaB6



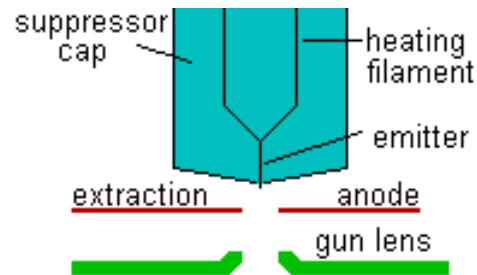


Electron Optics Basics – Sources FE





Electron Optics Basics – Sources TFE





Source Characteristics

Source Type	Brightness [amp/cm ² /str]	Source Size	Energy Spread	Vacuum Required (Torr)
Tungeston	10^5	25um	2-3eV	10^{-6}
LaB ₆	10^6	10um	2-3eV	10^{-8}
TFE	10^8	25nm	0.9eV	10^{-9}
Cold FE	10^9	5nm	0.22eV	10^{-10}





Electron Optics Basics - Brightness

$$\beta = J/\Omega \text{ [amps/cm}^2/\text{str]}$$

Where J is the current density [amps/cm²]

And Ω is the solid angle

For a “spherical tip source”

$$\beta = I/(\pi r \alpha)^2$$

Where r , it the radius and α is the half angle
in radians





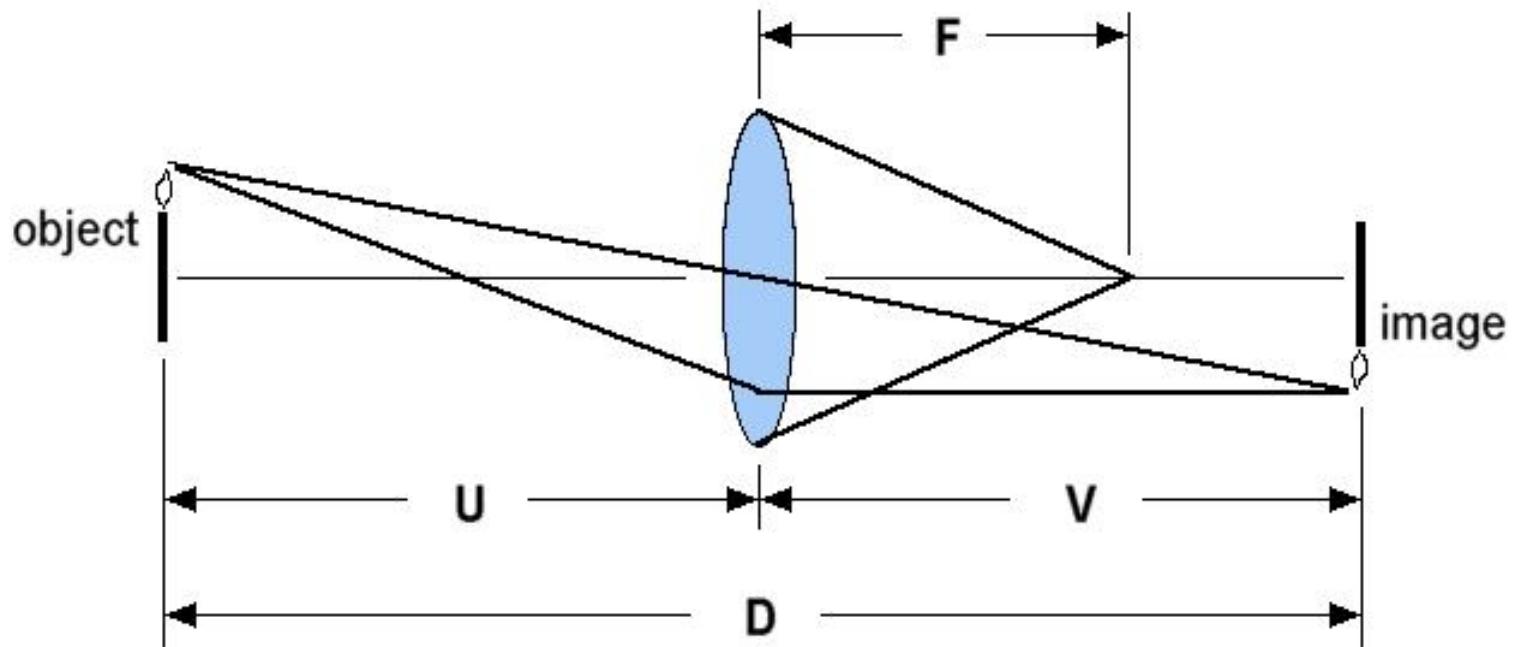
Electron Optics Basics - Brightness

- If the beam energy is constant, brightness is conserved or reduced by apertures
- This is a consequence of classical statistical mechanics where the volume of momentum position “phase space” is conserved (Liouville equation)
 - $dxdydzdp_x dp_y dp_z)_{\text{start}} = dxdydzdp_x dp_y dp_z)_{\text{end}}$





Electron Optics Basics – Lens Action





Geometrical Optics

- Thin Lens assumption i.e. $w \ll u, v, f$

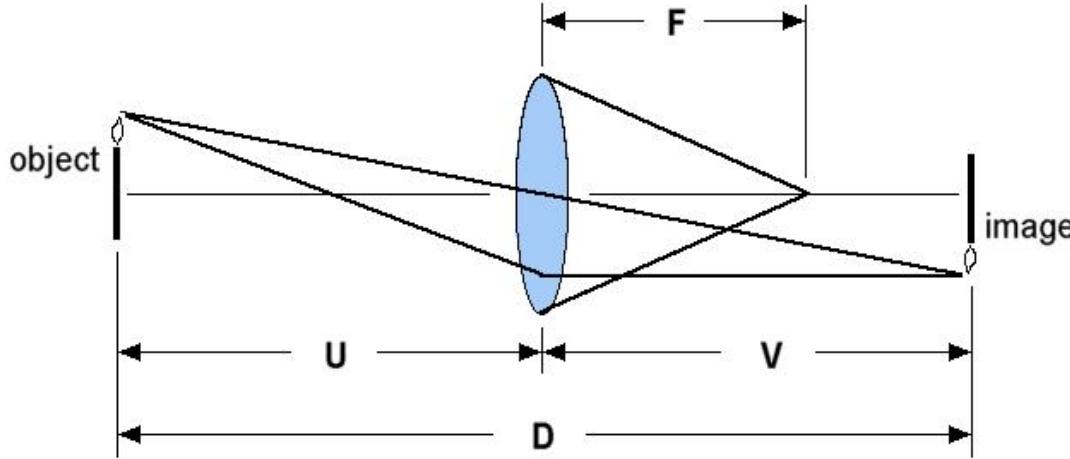
$$\frac{1}{u} + \frac{1}{v} = \frac{1}{f}$$

$$M = u/v$$





Brightness for a single thin lens system in small angle approximation



Small angle approximation:

$$\theta_1 = L_r/u \quad \theta_2 = L_r/v$$

$$2\pi(1 - \cos(\theta)) = \pi\theta^2$$

$$1/\Omega_1 I/d_1^2 =? 1/\Omega_2 I/d_2^2$$

$$\pi\theta_1^2 I/d_1^2 =? \pi\theta_2^2 I/d_2^2$$

$$v^2 d_1^2 =? u^2 d_2^2$$

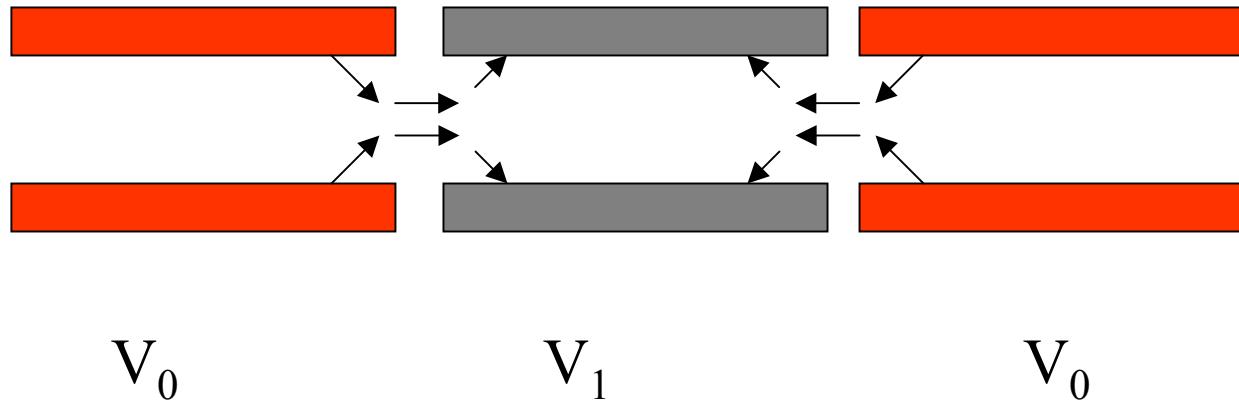
OK





Electron Optics Basics – Electrostatic Lens

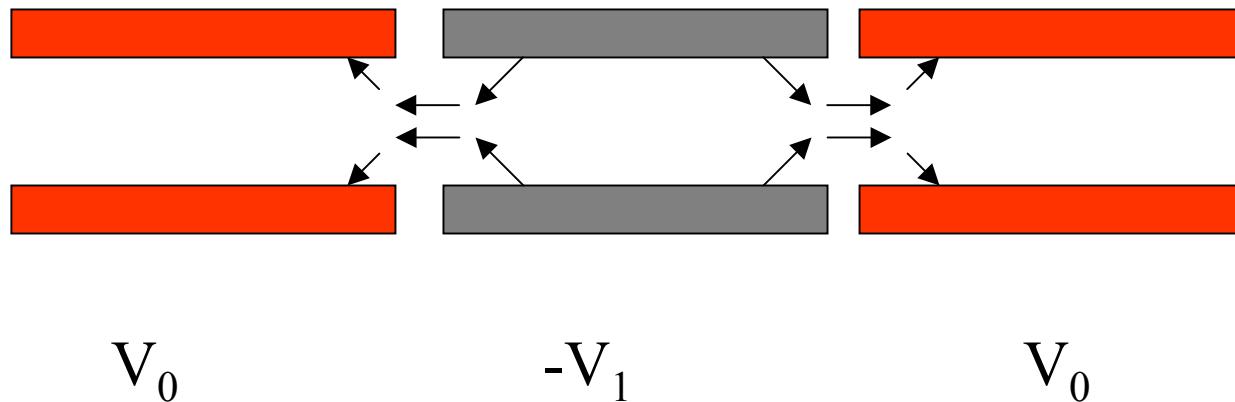
$$F = q(E)$$





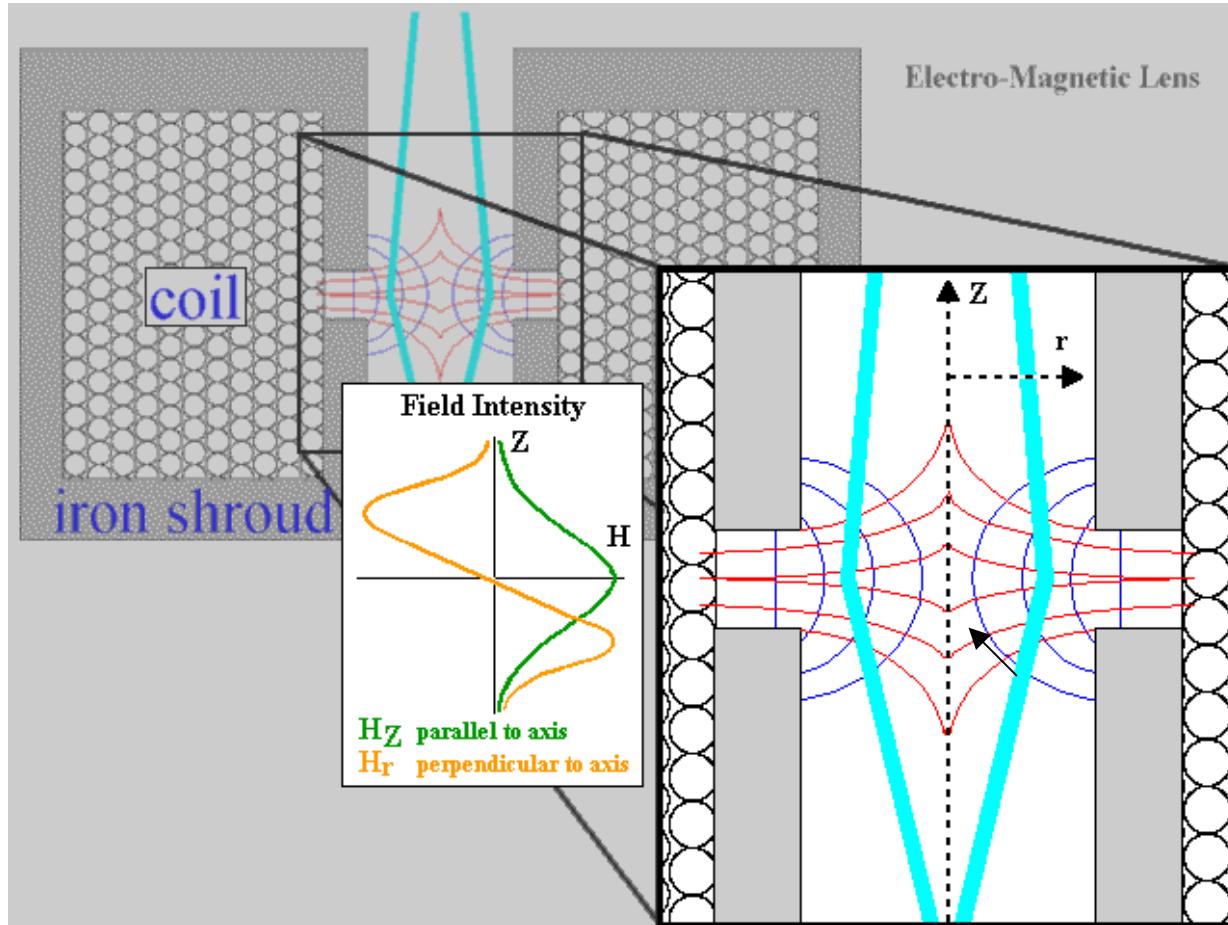
Electron Optics Basics – Electrostatic Lens

$$F = q(E)$$





Electron Optics Basics – Magnetic Lens



$$dp/dt = q(\mathbf{v} \times \mathbf{B})$$

$$f = KV/(NI)^2$$





Electron Optics Basics – Paraxial Equations for Magnetic Lens



- $\mathbf{F} = q(\mathbf{E} + \mathbf{v} \times \mathbf{B})$
 - $F_r = -ev_\theta B_z(z)$
 - $F_r = -(e^2/(4m))B^2r$
 - $\mathbf{F} = m\mathbf{a}$
 - $d^2r/dt^2 + (e^2/(4m)) B^2 r = 0$
 - $(1/2) m v_z^2 = eV$
 - $d^2r/dz^2 = -(e/(8m)) B^2 r/v_r$
-





Electron Optics Basics – Magnetic Lens

$$\mathbf{F} = q(\mathbf{E} + \mathbf{v} \times \mathbf{B}) \text{ (the Lorentz force)}$$

where F is the force,

q is the charge on the particle,

E is the electric field,

v the particle's velocity and

B is the magnetic field.





Electron Optics Basics – Aberrations

$$d_{sa} = C_s \alpha^3 / 2$$

where C_s = spherical aberration coefficient,
and α = semi angular aperture of the lens.

$$d_{di} = 0.61\lambda/NA = 0.61\lambda/\alpha \ (\lambda = 0.0037 \text{ nm for } 100\text{kV})$$

$$d_{ca} = C_c \alpha (\Delta V/V)$$

α = half (semi) angle





Electron Optics Basics – Estimating Current and Spot size

- Lens Aberrations
- $\Delta V/V$
- Brightness
- Estimate using a sum in quadrature

$$D_t^2 = (\text{source}/M)^2 + (d_{sa})^2 + (d_{di})^2 + (d_{ca})^2$$

$$I = \beta * (\pi \alpha d / 2)^2$$





Electron Optics Basics – Estimating Current and Spot size - Example

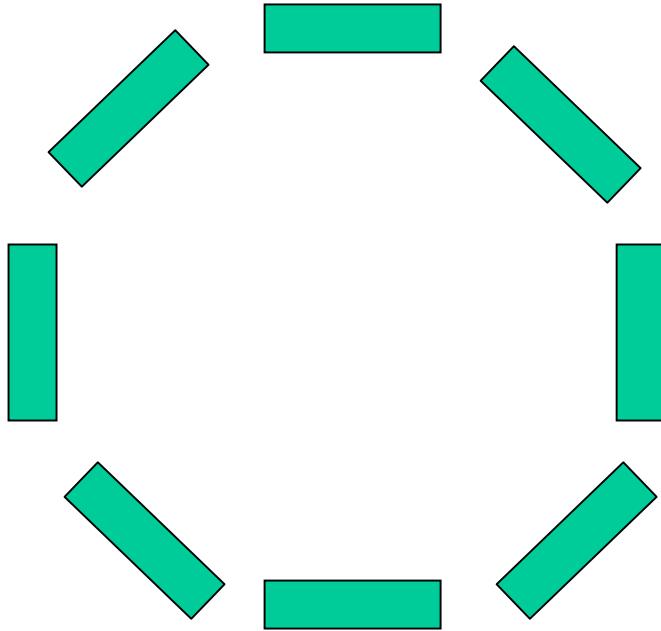
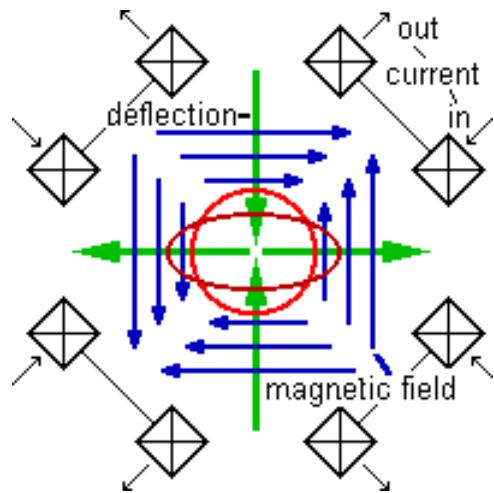
- Lens Aberrations
- $\Delta V/V$
- Brightness
- Estimate using a sum in quadrature

$$D_t^2 = (\text{source}/M)^2 + (d_{sa})^2 + (d_{di})^2 + (d_{ca})^2$$





Electron Optics Basics – Stigmator / Deflector





Electron Optics Basics – Static Field Equations

Description of equation	Electric fields	Magnetic fields
Force	$\mathbf{F} = Q\mathbf{E}$	$d\mathbf{F} = (\mathbf{I} \times \mathbf{B}) dl$ $\mathbf{F} = Q_m \mathbf{B}$
Basic relations for lamellar and solenoidal fields	$\nabla \times \mathbf{E}_c = 0^\dagger$	$\nabla \cdot \mathbf{B} = 0$
Derivation from scalar or vector potential	$\mathbf{E}_c = -\nabla V$ $V = \frac{1}{4\pi\epsilon_0} \int_v \frac{\rho}{r} dv$	$\mathbf{B} = \nabla \times \mathbf{A}$ $\mathbf{A} = \frac{\mu_0}{4\pi} \int_v \frac{\mathbf{J}}{r} dv$
Constitutive relations	$\mathbf{D} = \epsilon\mathbf{E}$	$\mathbf{B} = \mu\mathbf{H}$
Source of electric and magnetic fields	$\nabla \cdot \mathbf{D} = \rho$	$\nabla \times \mathbf{H} = \mathbf{J}$
Energy density	$w_e = \frac{1}{2}\epsilon E^2 = \frac{1}{2}ED$	$w_m = \frac{1}{2}\mu H^2 = \frac{1}{2}BH$
Capacitance and inductance	$C = \frac{Q}{V}$	$L = \frac{\Lambda}{I}$
Capacitance and inductance per unit length of a cell	$\frac{C}{d} = \epsilon$	$\frac{L}{d} = \mu$
Closed path of integration	$\oint \mathbf{E} \cdot d\mathbf{l} = \nabla V$ $\oint \mathbf{E}_c \cdot d\mathbf{l} = 0$	$\oint \mathbf{H} \cdot d\mathbf{l} = F = NI$ $\oint \mathbf{H} \cdot d\mathbf{l} = 0 \quad \text{no current enclosed}$
Derivation from scalar potentials	$\mathbf{E}_c = -\nabla V$	$\mathbf{H} = -\nabla U \quad \text{in current-free region}$

† \mathbf{E}_c is the static electric field intensity (due to charges). \mathbf{E} (without subscript) implies that emf-producing fields (not due to charges) may also be present.





Electron Optics Basics – Lens Field Equations

- Electrostatic – charge free Laplace equation
 - $\nabla^2\Phi = -\rho/\epsilon = 0$
 - $\mathbf{E} = -\nabla\Phi$
- Magnetic Potential
 - $\nabla \times \mathbf{A} = \mathbf{B}$
 - $\nabla^2\mathbf{A} = -\mu\mathbf{J}$
 - $\mathbf{H} = -\nabla U$





Electron Optics Basics – Solutions

Procedure to solve Electron Optics Problems

- Define the geometry of the lens
- Solve the Laplace equation Using finite element or difference methods, i.e. solve a very large but sparse matrix
- Integrate the trajectories
- Plot and summarize the results
- Demo





Electron Optical Layout for the Leica VB6

